

**INVESTIGATION OF CARBONATED WATER INJECTION
(CWI) AS AN EOR TECHNIQUE FOR LIGHT OIL
(CONDENSATE OIL) RESERVOIR**



Session: Fall-19

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Certification

This is to certify that **Wasi Ullah, [51172]** and **Abdul Wadood, [51311]** have successfully completed the final project **Investigation of Carbonated water injection as an EOR Technique for light oil reservoir**, at the **Balochistan University of Information Technology, Engineering & Management Sciences, Quetta**, to fulfill the partial requirement of the degree **BS Petroleum & Gas Engineering**.

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**Investigation of Carbonated water injection as an EOR Technique for light oil
reservoir**

Sustainable Development Goals

(Please tick the relevant SDG(s) linked with FYDP)

SDG No	Description of SDG	SDG No	Description of SDG
SDG 1	No Poverty	SDG 9	Industry, Innovation, and Infrastructure ✓
SDG 2	Zero Hunger	SDG 10	Reduced Inequalities
SDG 3	Good Health and Well Being	SDG 11	Sustainable Cities and Communities
SDG 4	Quality Education	SDG 12	Responsible Consumption and Production
SDG 5	Gender Equality	SDG 13	Climate Change
SDG 6	Clean Water and Sanitation	SDG 14	Life Below Water
SDG 7	Affordable and Clean Energy ✓	SDG 15	Life on Land
SDG 8	Decent Work and Economic Growth	SDG 16	Peace, Justice and Strong Institutions
		SDG 17	Partnerships for the Goals



Range of Complex Problem Solving			
	Attribute	Complex Problem	
1	Range of conflicting requirements	Involve wide-ranging or conflicting technical, engineering and other issues.	
2	Depth of analysis required	Have no obvious solution and require abstract thinking, originality in analysis to formulate suitable models.	
3	Depth of knowledge required	Requires research-based knowledge much of which is at, or informed by, the forefront of the professional discipline and which allows a fundamentals-based, first principles analytical approach.	
4	Familiarity of issues	Involve infrequently encountered issues	
5	Extent of applicable codes	Are outside problems encompassed by standards and codes of practice for professional engineering.	
6	Extent of stakeholder involvement and level of conflicting requirements	Involve diverse groups of stakeholders with widely varying needs.	
7	Consequences	Have significant consequences in a range of contexts.	
8	Interdependence	Are high level problems including many component parts or sub-problems	
Range of Complex Problem Activities			
	Attribute	Complex Activities	
1	Range of resources	Involve the use of diverse resources (and for this purpose, resources include people, money, equipment, materials, information and technologies).	
2	Level of interaction	Require resolution of significant problems arising from interactions between wide ranging and conflicting technical, engineering or other issues.	
3	Innovation	Involve creative use of engineering principles and research-based knowledge in novel ways.	
4	Consequences to society and the environment	Have significant consequences in a range of contexts, characterized by difficulty of prediction and mitigation.	
5	Familiarity	Can extend beyond previous experiences by applying principles-based approaches.	

Abstract

This research investigates CO₂ solubility in various systems, emphasizing its relevance to enhanced oil recovery (EOR) and carbon capture and storage (CCS). The study explores CO₂ behavior in deionized water, brine, condensate light oil, and CO₂+CH₄ in water and oil. It scrutinizes factors like temperature, pressure, and stirring, finding increased CO₂ solubility with pressure and reduced solubility with temperature in CO₂-oil and CO₂+CH₄-oil systems. Stirring enhances CO₂ dissolution. Optimal pressure and temperature settings for maximum CO₂ solubility and swelling factor are identified. CO₂ solubility in brine increases significantly with pressure in the CO₂-Brine system, plateauing at higher pressures. Diffusion, particularly with gaseous CO₂, plays a crucial role influencing solubility in oil. The study offers practical insights into optimizing EOR and CCS processes.

Keywords: Carbon capture and storage CCS; Diffusion; Enhanced oil recovery EOR; Swelling factor

Undertaking

I certify that the project **Investigation of Carbonated water injection as an EOR Technique for light oil reservoir** is our own work. The work has not, in whole or in part, been presented elsewhere for assessment. Where material has been used from other sources it has been properly acknowledged/ referred.

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Chapter 1

1.1 Introduction

The study explores the significance of understanding carbon dioxide (CO₂) solubility in crude oil and brine systems, crucial for enhanced oil recovery (EOR) and carbon capture and storage (CCS). CO₂, a major greenhouse gas contributing to global warming, necessitates effective management of its emissions. In EOR, injecting CO₂ into oil reservoirs enhances recovery by altering viscosity and increasing pressure, with solubility in crude oil being pivotal. Factors like temperature, pressure, and mixing conditions influence CO₂ solubility, guiding EOR optimization. Simultaneously, the rising global energy demand (35.5% by 2039) emphasizes crude oil's continued dominance, contributing 26% to global energy transportation. However, fossil fuel use heightens anthropogenic greenhouse gases, urging a 49-79% reduction in global emissions by 2052 to avert catastrophic climate effects. [1]

The passage discusses enhanced oil recovery (EOR) methods using gases like carbon dioxide (CO₂), methane, and nitrogen, with a focus on gas flooding. Immiscible CO₂ readily dissolves in oil, enhancing hydrocarbon recovery by reducing viscosity and inducing hydrocarbon swelling, particularly beneficial in permeable oil reservoirs. Miscible flooding, termed "miscible flooding," occurs when gas or oil is miscible. CO₂, due to its lower cost and minimum miscibility pressure, is commonly used in miscible displacement. The discussion extends to the solubility of CO₂ in brine, emphasizing its impact on recovery in carbonated water injection applications. The solubility is influenced by pressure, temperature, and salinity, with higher solubility enhancing displacement efficiency. Additionally, the solubility of CO₂ in the oil phase is explored, highlighting its relation to oil characteristics, such as density and mobility, with increased CO₂ content leading to reduced viscosity and improved recovery. Solubility tests reveal specific CO₂ solubilities in brine and oil under defined conditions. [2-4]

From 2010 to 2040, the global energy demand is anticipated to rise by almost 35%. The primary source of energy will continue to be crude oil, which will add around 25% more to the global energy supply. [5]

Between 2008 and 2035, the output of hydrocarbon liquids must increase by 26.6 million barrels per day in order to meet the rise in global demand for crude oil. [6]

Experimental data on the solubility of carbon dioxide (CO₂) in pure water and aqueous solutions containing sodium hydroxide are reported for a temperature range of 293.15 to 393.15 K and pressures up to 5 MPa. [7]

CO₂ Mass Transfer at High Pressures in a Carbonated Water–Oil System [8] This study focuses on the experimental measurement of pressure buildup in a closed water-oil system. The obtained pressure data is then utilized to develop a mathematical model, allowing for the calculation of diffusion coefficients of carbon dioxide (CO₂) in a carbonate water-oil system.

Utilizing Carbonated Water Injection (CWI) as a method of enhanced oil recovery in light oil systems: evaluation of the recovery process at the pore scale [9] Through a series of lab experiments and computer simulations, the performing of secondary and tertiary carbonated water injection (CWI) at numerous operational circumstances was examined in this study. According to the results of CO₂ solubility tests conducted at constant temperatures, both the water and oil phases show an increase in solubility when the pressure rises in the P = 700KPA – 11000 KPa range.

However, it has been because of CO₂ mobility relative to petroleum and gravity separation (override) due to sizable disparity in the densities of CO₂ also an oil led to an oil volumetric efficiency during the displacement of reservoir through EOR. These problematic wonders in pure CO₂ flooding led to a large residual oil saturation also an early CO₂ breakthrough. While gas injections are still using in oil recovery due to its easiness, other recovery methods have been created (and used) at lab., pilot, and field balances to address mentioned difficulties during the pure CO₂ flooding. These methods include water alternating gas (WAG), simultaneous water alternating gas (SWAG), CO₂ foam injection, and CWI. [10]

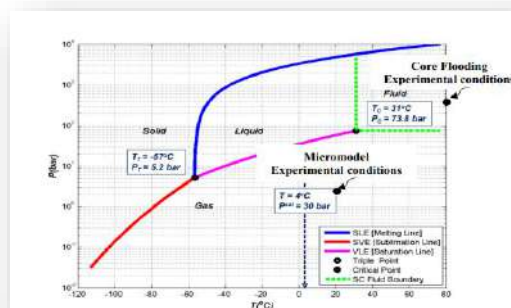


Figure 1-1 CO₂ phase diagram as a function of pressure and temperature [11]

The solubilities (molality%) of CO₂ in pure water (a) and brine are depicted by red curves (b, c, and d), with each contour representing a system bubble curve at various saturation pressures (0.1, 0.6, 1.1, 1.5, 2.1, 1050, 2050, 2550, 4050, 5050 & 7050 gr/mol) and temperatures (31°C, 61°C, 90.5°C for pure water; 31°C, 60°C, 90°C for brine with different concentrations). In the CO₂-H₂O-brine system, the contours illustrate solubilities in a Pressure-Temperature diagram, where the water solution is in constant equilibrium. Oil solubility of CO₂ is crucial for oil recovery during CO₂ injection, influencing miscibility and enhancing oil mobility through oil swelling and viscosity reduction. The experimental setup, utilizing a rotating furnace and a custom-designed reaction cell, ensures precise control of temperature and pressure for accurate measurements of CO₂ solubility in water and brine. [12-14]

1.2 Statement of the problem

After secondary recovery the tertiary recovery method will be used. But the tertiary recovery method is very costly compared to the recovery of hydrocarbons. In EOR method the CO₂ injection is also costly method. For Miscible injection the solubility of CO₂ is not much more soluble in low pressure.

The diffusion between carbonated water and light oil is also a great issue.

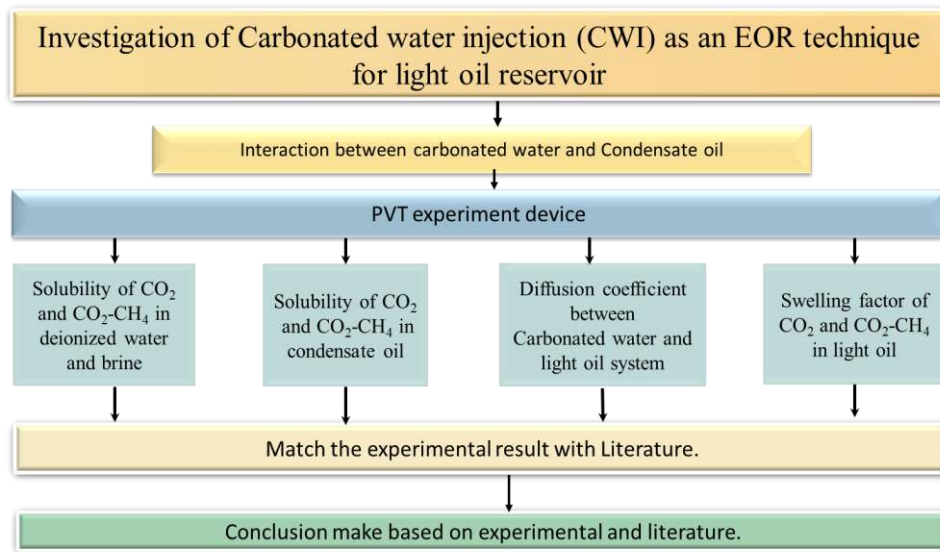
1.3 Goals/Aims & Objectives

The major goal of this study was to ascertain whether the CWI technique might be used to improve oil recovery under varied operating circumstances.

- “To investigate the solubility of CO₂ with Water and oil by injecting some chemical materials to increase solubility “
- Under varied working circumstances, the viscosity, density, and asphaltene content of the brine and oil samples were measured.

- Researchers examined the phase properties of CO₂-water, CO₂-brine, and CO₂-oil systems, which are all CO₂-CH₄-saturated systems. This was accomplished through a series of measurements of CO₂ solubility in pure water, brine, and crude oil. Effects of several operational parameters (such as pressure and temperature) and brine salinity were shown to have an impact on CO₂ solubility in pure water and brine.
- Also, CH₄ will be Used also with CO₂ To find their solubility.
- Tests were carried out in secondary and tertiary systems at various operating pressures, temperatures, injection rates, and carbonation levels to assess the performance of CWI. Additionally, data analysis, conclusion interpretation, and outcome comparisons were done.
- Determine a comprehensive phase behavior model that can simulate different aspects of the oil and brine samples' interactions with CO₂ under varied operating situations.
- Use a compositional simulator to incorporate the EOS-based fluid model to simulate laboratory displacement tests.
- To evaluate the diffusion of CO₂-CH₄ in condensates oil and in DI Water.

1.4 Methods



1.5 Report Overview

The "Introduction," which comprises the background, problem statement, goals and objectives, technical approach, and thesis structure, is the main topic of the first chapter. The literature review in the second chapter, which is devoted to Carbonated water injection research, contains all this material. The third chapter, "Material and Methodology," focuses on the tools required for our research projects as well as the order in which the experiments must be carried out. The "Results and Discussion" section of the research materials is included in the fourth chapter. "Conclusion and Recommendations," the fifth and final chapter, contains a summary of the dissertation and suggestions for further research, respectively.

Chapter 2

2.1 Materials and Methodology

The purpose of the methodology chapter in the thesis titled "Carbonated water injection as an Enhanced Oil Recovery (EOR) Technique for light oil reservoirs" is to outline the experimental procedures and methods utilized in the research. The setup, sample preparation, experimental protocol, data collecting and analysis, safety precautions, and study constraints are all thoroughly described in this chapter. It serves to ensure the transparency and reproducibility of the research methodology employed in investigating the effectiveness of carbonated water injection as an EOR technique for light oil reservoirs.

The research project focuses on investigating the solubility of carbon dioxide (CO_2) in various scenarios, including CO_2 in deionized water, CO_2 in brine, CO_2 in condensate light oil, and the solubility of CO_2 combined in methane (CH_4) in both water and oil. Additionally, the diffusion behavior of CO_2+CH_4 in water and condensate is another objective of the study.

The rationale for utilizing carbonated water injection as an Enhanced Oil Recovery (EOR) technique for light oil reservoirs is driven by the following considerations. Firstly, light oil reservoirs present challenges for conventional oil recovery methods due to their low permeability and limited natural energy sources. Therefore, exploring alternative EOR techniques is essential to maximize oil extraction from these reservoirs. Carbonated water injection offers potential advantages for EOR in light oil reservoirs. By dissolving CO_2 in water, a multiphase flow is created, leading to improved displacement efficiency and increased oil mobilization. The CO_2 dissolution reduces the viscosity of the oil, facilitating its flow through the reservoir. Moreover, carbonated water injection can promote reservoir rock swelling, further enhancing oil recovery. Importantly, carbonated water injection is considered an environmentally friendly EOR method. It involves capturing CO_2 , a greenhouse gas responsible for climate change, and utilizing it in the process, thereby reducing its release into the atmosphere. By investigating the solubility of CO_2 in different scenarios and its diffusion behavior, this research contributes to understanding the fundamental aspects of carbonated water injection as an EOR technique for light oil reservoirs.

The primary research objectives include determining the solubility of CO₂ with water, brine, and condensate light oil. Additionally, investigating the solubility of CO₂ combined with CH₄ in both water and oil is a focus. Another objective is to analyze the diffusion behavior of CO₂+CH₄ in water and condensate. By addressing these objectives, the research aims to provide insights into the solubility and diffusion characteristics of CO₂ in various scenarios, contributing to the knowledge base of carbonated water injection as an EOR technique for light oil reservoirs.

2.1.1 Preparation of Brine

In this research we will use the PVT cell. Our main tool for this research is PVT cell. In this we must investigate the solubility of CO₂ in water and Light oil (condensate oil) and then also CO₂ solubility with combination of CH₄ . then the diffusion of CO₂ will be investigated.

In this research, we used CO₂ as an injected gas. We have a 100cc cell PVT we inject 25ml deionized water & then 75cc CO₂ gas were injected at a pressure of 105psi. the through the pump we pressurize the gas in the cell and its volume becomes less. If we reached a pressure of 1029psi the volume becomes 25ml & the gas has dissolved in water. The pressure & volume is noted at various stages of the experiment & be shown in table 3-1. For the 613 psi, we inject another gas & fill the 100cc cell of PVT. The CO₂ volume at 105psi was 525cc but on the 613psi it became less up to 75cc. The other table and graph ranges from 615psi to 2200psi, and the volume was noted & also the volume on 2200psi is 35.134cc. and maximum percentage of CO₂ is solved in the deionized water. Up to the initial phase, we have done these two experiments.

2.1.2 Scheme (1)

Table 2-1 Table of PVT experiments of CO₂+CH₄-light oil and water interactions

No	Contents	Temperature °C	Pressure	Experimental Target	Remarks	Number of Experiments
1	PVT Data	25-70 °C	1-7 MPa	Critical pressure and temperatures, solubility, swelling factor Oil composition and properties of each component		5

2	Interaction between water-CO ₂	20-60 °C	1-7 MPa	CO ₂ +CH ₄ , Solubility, diffusion coefficient at different concentration of brine		6
3	Interaction between oil-CO ₂ +CH ₄	20-50 °C	1-7 MPa	Solubility, diffusion coefficient, swelling factor		5
Total Experiments						16

2.1.3 Scheme (2)

Table 2-2 Scheme for PVT experiments of CO₂+CH₄ diffusion in condensate oil

No	Contents	Temperature °C	Pressure MPa	Experimental Target	Remarks	Number of Experiments
1	CO ₂ Diffusion in water	30-50°C	1-8 MPa	To evaluate Diffusion of CO ₂ in water by various parameters of solubility and mole fraction		1-2
2	CO ₂ Diffusion in light oil	25-60°C	1-8 MPa	To evaluate Diffusion of CO ₂ in oil by various parameters of solubility and mole fraction		1-2
3	CO ₂ +CH ₄ Diffusion in light oil	25-55°C	1-8 MPa	To evaluate Diffusion of CO ₂ +CH ₄ in oil by various parameters of solubility and mole fraction		1-3
Total						3-5

2.2 Experimental setup

2.2.1 Specification of PVT

1. Maximum Pressure: The PVT cell had the capability to handle a maximum pressure of 10,000 pounds per square inch (psi). This high-pressure tolerance was essential to simulate conditions found in reservoirs and ensure the integrity of the cell during the experiments.
2. Maximum Temperature: The PVT cell was designed to withstand a maximum temperature of 180 degrees Celsius. This temperature range was necessary to replicate the conditions encountered in oil reservoirs and assess the behavior of the system at elevated temperatures.
3. Cell Volume: The PVT cell had a volume capacity of 100 cubic centimeters (cc). This volume allowed for the introduction of the necessary components,

such as water, carbon dioxide, brine, and condensate light oil, to investigate their solubility and behavior within the system accurately.

4. **Cell Dimensions:** The PVT cell had a height of 12 centimeters (cm) and a width of 2.56 cm. These dimensions provided a suitable space for the experimental setup, accommodating the required volume of the components and ensuring proper circulation and mixing during the experiments.

The PVT cell was equipped with pressure, volume, and temperature measuring sensors. These sensors played a crucial role in monitoring and recording the changes in pressure, volume, and temperature within the cell during the experimental procedures. Accurate measurements of these parameters were essential for analyzing the behavior and performance of the system under various conditions.

2.2.2 Selection criteria for PVT

1. **Pressure and Temperature Range:** The PVT cell needed to have a maximum pressure rating capable of withstanding the desired experimental conditions. Similarly, it was essential to choose a cell with a maximum temperature tolerance that aligned with the anticipated temperature range during the study. These specifications were crucial for accurately simulating the conditions found in light oil reservoirs.
2. **Volume Capacity:** The PVT cell's volume capacity was an important consideration as it needed to accommodate the required number of components, such as water, CO₂, brine, and condensate light oil. Sufficient volume capacity ensured that the experiments could be conducted with representative quantities of the substances under investigation.
3. **Dimensions:** The dimensions of the PVT cell played a role in determining its compatibility with the experimental setup. Adequate height and width dimensions were necessary to accommodate the required volume while allowing for proper circulation and mixing of the components.

2.2.3 Data collection

2.2.3.1 Properties and Composition of Condensate oil:

Table 2-3 The Physical and chemical properties of condensate oil used in this study

Properties of condensate oil can be defined as below:

PARAMETERS	TEST RESULTS
Sp. Gravity @ 60/60 °F	0.7366
BS & W, Vol.%	<0.05
Sulphur Content, Wt.%	0.007
Water Vol%	<0.05
Salt Content, lb/1000bbl	Nil
Kinematic Viscosity at 40 °C, cSt	0.713
Kinematic Viscosity at 50 °C, cSt	0.664
Pour Point, °C	<-24
Con. Carbon Residue, Wt.%	0.024
Color ASTM	2.5
Reid Vapor Pressure (RVP) @ 100 °F. psi	7.2
Calorific Value (Gross), Btu/lb	20255
Calorific Value (Net), Btu/lb	18896
I.B.P	49
5/10.% Recovery °C	70/80
20/30.% Recovery °C	89/96
40/50 % Recovery °C	106/116
60/70% Recovery °C	126/141
80/90% Recovery °C	165/203
95% Recovery °C	234
End Point C	267
Barrel M/Ton	8.51
TBP CUTS	Vol%/wt.%
0 deg * C to * 0.4 deg * C (Loss)	9.80/9.59
40 deg * C to 155 deg * C (Naphtha)	67.40/66.15
155 deg * C to 235 deg * C (Kerosene)	18.15/18.95

2.2.4 Procedure of PVT Cell for Solubility Measurement

The PVT (Pressure-Volume-Temperature) cell is commonly used to measure the solubility of gases in liquids, including hydrocarbon liquids such as light oil.

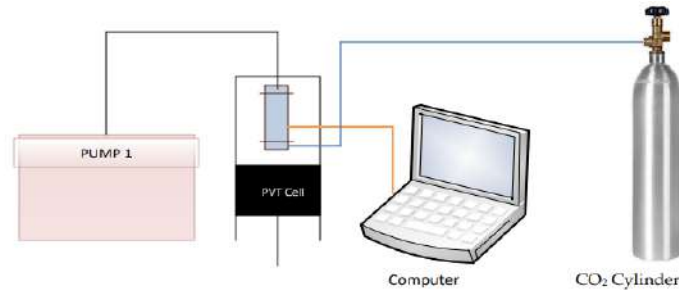


Figure 2-1 Experimental Setup for PVT studies of CO₂+ CH₄ with water/ light oil

The procedure for conducting solubility measurements using a PVT cell typically involves the following steps:

1. Sample Preparation:
 - Obtain a representative sample of the light oil to be studied.
 - Ensure that the sample is properly collected, preserved, and representative of the reservoir conditions.
 - Remove any impurities or contaminants that may affect the solubility measurements.
2. PVT Cell Assembly:
 - Prepare the PVT cell according to the manufacturer's instructions.
 - Clean and dry the PVT cell thoroughly to eliminate any residual contaminants.
 - Install appropriate pressure and temperature sensors on the cell.
 - Ensure that the cell is properly sealed to prevent any leakage during the experiment.
3. Calibration:
 - Calibrate the pressure and temperature sensors using known reference values.
 - This step is crucial to ensure accurate measurements during the solubility experiment.

4. Equilibration:

- Transfer a measured quantity of the light oil sample into the PVT cell.
- Introduce the desired gas (e.g., CO₂ or CH₄) into the cell at a specified pressure and temperature.
- Allow the system to reach thermodynamic equilibrium by allowing sufficient time for gas-liquid equilibration.
- Stir or agitate the mixture gently to enhance the solubility equilibrium.

5. Pressure and Volume Measurements:

- Measure the pressure and volume of the system after equilibration.
- Record the values obtained from the pressure and volume sensors.

6. Solubility Calculation:

- Calculate the solubility of the gas in the light oil using the obtained pressure and volume data.
- Consider the ideal gas law, Henry's law, or other appropriate models to determine the solubility at the given conditions.

7. Data Analysis:

- Analyze and interpret the solubility data obtained from the experiment.
- Compare the results with previous studies or expected values for validation and verification purposes.

2.3 Materials

2.3.1 Condensate oil

Condensates often include little to no polycyclic aromatic hydrocarbons (PAH), which are typically present in crude oils, and are primarily made up of alkanes (saturated hydrocarbons like butane, pentane, and hexane). Condensates are highly volatile and have a very low water solubility.

2.3.2 PVT Cell:

Following SOPs are Conducted to perform the Experiment.

1. Vacuum the apparatus and introduce the Sample into PVT cell according to the sample transferring SOPs.

2. Create extreme conditions of pressure and temperature. (i-e Reservoir Conditions).
3. Selected pressure and temperature conditions by using a software “Fluid Eval.”
4. Open FLUID EVAL software. Select pressure from Pressure set point with our required Pressure ramp 100 psi/min, similarly temperature from temperature set point that we have given 30 C.

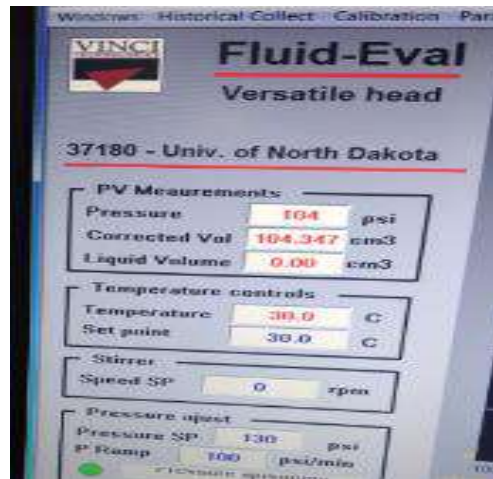


Figure 2-2 Pressure set point

5. Start stirrer to mix the sample if needed up to 20000 RPM.
6. The pressure, temperature increment and volume of sample can be seen on software window.
7. When the required conditions of pressures and temperatures are achieved, wait for some time, so that pressure is stabilized.
8. Prepare the Macro for excel for this go to C drive of PC, then follow these steps : C drive > Applilab > project > Fluid Eval Educ versatile > Excel files > CMD gas report blank.
9. Open CMD (constant mass depletion) gas field. Set stability criteria first then provide pressure increment profile in pressure set point column.(i.e we have given 613,809,1007,1198,1398,1599,1800,2000,2200)
10. Take temperature constant 30 C.
11. Save the file after completion of experiment in the same location.

2.4 Representative and quality of samples

To ensure the representativeness and quality of the samples, a comprehensive sampling plan was developed, taking into account the specific parameters and locations relevant to the research objectives. Rigorous sampling techniques, such as random sampling and stratified sampling, were employed to collect a diverse range of samples from the target reservoirs. Special attention was given to maintaining sample integrity during collection, with sterile containers used to minimize contamination risks.

2.4.1 Step by step procedure;

The experimental procedure involved several sequential steps, as outlined below:

1. Preparation of the PVT Cell: The PVT cell was emptied and thoroughly dried using a vacuum pump to ensure a clean and dry environment for the experiment.
2. Software Setup: The necessary software for data acquisition and analysis was prepared and set up to facilitate accurate and efficient data recording.
3. Injection of DI Water and CO₂: A precise volume of 25 ml of deionized (DI) water was injected into the PVT cell. Subsequently, 75 ml of CO₂ was injected from a CO₂ cylinder into the cell under the desired pressure conditions.
4. Application of Pressure: The pump was activated to exert pressure on the cell, ensuring the desired experimental conditions were achieved.
5. Setting Pressure and Temperature: The pressure was set within the range of 500 psi to 3500 psi, while the temperature was maintained at 40°C, as per the predetermined experimental parameters.
6. Pressure and Volume Measurements: The pressure and volume values were recorded at regular intervals, typically after a 15-psi change in pressure. These measurements were manually noted and simultaneously captured by the software, creating a graphical representation of the data.
7. Repetition of Experiments: The solubility experiments were performed following the same procedure, with variations in pressure and temperature conditions, allowing for a comprehensive analysis of solubility behavior.

By following this step-by-step procedure, the experiment ensured consistent and systematic data collection, enabling accurate analysis and interpretation of the solubility experiments.

The experimental setup involved the utilization of a PVT (Pressure, Volume, Temperature) cell at the PVT Lab JICA Hall BUITEMS. The dimensions of the cell were 10 cm in height and 2.56 cm in diameter. Initially, the system comprised only water as the pure component. To initiate the experiment, the cell was partially filled with normal water, accounting for 25% of its volume. Subsequently, a vacuum was applied, and the liquid volume under saturated conditions was determined to calculate the initial moles of water present. Then the carbon dioxide was injected with a specific pressure. Once this point was established, the experiment commenced by monitoring the pressure, temperature, and liquid level injected volume progressively decreased. Pressure readings were manually recorded at specific time intervals, while a strip chart continuously captured pressure data. The software facilitated the measurement of the liquid level throughout the experiment.

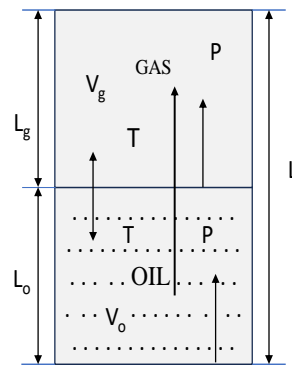


Figure 2-3 Schematic process of Diffusion of CO_2 in light oil or in water through PVT cell

2.5 Safety measures

- To prioritize the safety of personnel and the protection of the PVT equipment, several precautionary measures were implemented throughout the experimental procedures. These measures aimed to mitigate potential risks and ensure the well-being of the researchers and the environment.
- Personal protective equipment (PPE), including gloves, facemasks, and cotton lab coats, were utilized by all researchers involved in the experiments. These measures were taken to minimize direct contact with chemicals and ensure the safety of personnel during handling and manipulation of substances.

- In addition to the use of PPE, the researchers worked under the supervision of an expert lab assistant experienced in PVT operations. This provided guidance and support in adhering to safety protocols, handling equipment appropriately, and promptly addressing any unforeseen issues that could pose a risk.
- Furthermore, the project was conducted under the guidance and supervision of a designated supervisor who played a crucial role in ensuring the safety of the equipment. The supervisor monitored the experimental setup, reviewed safety procedures, and provided guidance in maintaining a safe working environment.
- By implementing these safety precautions, including the use of appropriate PPE and working under expert supervision, potential risks were mitigated to safeguard the well-being of the researchers and to protect the sensitive PVT equipment. These measures aimed to prevent accidents, minimize exposure to hazardous materials and, create a safe working environment conducive to conducting the experiments effectively and securely.

Chapter 3

3.1 Results and discussion

3.1.1 CO₂ Solubility in DI water and brine

In my experimental inquiry, the CO₂ solubility in salt-water with a salinity of $s = 0.3492$ mole NaCl/kg H₂O was studied on five pressures and uniform temperatures. The calculated CO₂ solubility in salt-water is shown in Fig. 4-3 for various temperatures ($T = 27$ °C and $T = 50$ °C) and pressure ranges. The experimental results and the estimated values generated by this experiment were in good agreement. An upgraded model was used. The estimated average relative variation between experimental and computed solubility values was 7.1%.

With equilibrium pressure, solubility of Carbon dioxide in salt water of 5 wt.% rises sharply until a certain point. CO₂ solubility in salt-water does not significantly rise with repeated increases in the equilibrium pressure, though. This behavior is related to the phase change of CO₂, which occurs at the CO₂ liquefaction pressure, P_{liq} , from a gas to a liquid. The process of dissolving CO₂ involves molecular diffusion, and the diffusion coefficient of CO₂ in gaseous form in salt-water is suggestively advanced than that of liquid CO₂. As a result, increased CO₂ dissolution in saline is restricted at compressions above the CO₂ liquefaction pressure. Nonetheless, at constant temperature { $T = 27$ °C }, the sensitivity of solubility of Carbon dioxide in salt-water to pressure reduces as pressure increases (e.g., Pressure greater than 6.91 MPa).

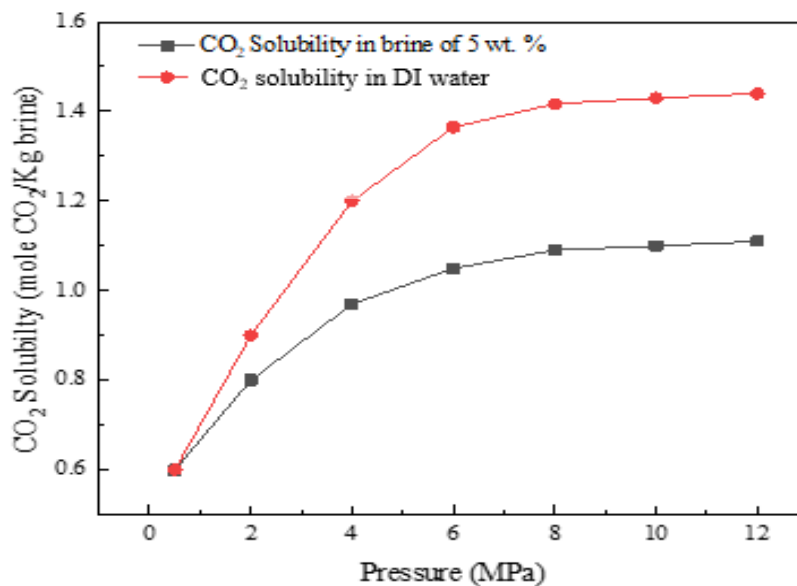


Figure 43-1 Measured and Calculated solubility of CO₂ in DI water & brine of 5 wt. % of salt.

One interesting discovery is that carbon dioxide in gaseous form is more soluble in condensate oil than Carbon dioxide in liquid phase. This discrepancy can be ascribed to gaseous CO₂ molecules having a larger diffusion coefficient due to their higher molecular motion amplitude. Gaseous CO₂'s enhanced mobility allows it to move more freely, interact with the interface of condensate oil, and permeate into the oil phase at a quicker pace. The model sought to offer a full knowledge of CO₂ solubility in oil and accurate predictions based on the stated input variables by including these parameters. The use of genetic algorithms enabled the model's predictive skills to be optimized and refined, improving its accuracy and dependability.

3.1.2 CO₂+CH₄ solubility in condensate Oil

CO₂ and CH₄ in a 50/50 moles% mole ratio provide a higher degree of graph cure than CO₂ alone. Pressures of eight different ranges and temperatures {T = 27 °C and 50 °C} were used to study the solubility of carbon dioxide and methane combine in oil. The determined solubility of CO₂ in crude oil is plotted against equilibrium pressure values for T = 25 and 50 degrees Celsius in the figure. With equilibrium pressure, the solubility of carbon dioxide was measured in crude oil rose. Henry's Law states that the amount of soluble carbon dioxide is influenced by the partial pressure of CO₂. The amount of CO₂ molecules that strike the interface of condensate oil is determined by fractional pressure.

Various factors were discovered to influence solubility of carbon dioxide in condensate oil. It was discovered that increasing the number of collisions between CO₂ and oil molecules resulted in a greater amount of dissolved CO₂ and, as an output, high Carbon dioxide solubility values. In contrast, rising temperatures reduced CO₂ solubility in crude oil. e.g. at equilibrium pressures at P = 7000 KPa, CO₂ dissolution declined from b = 28.95 gr CO₂/100 gr of condensate oil to b = 22.0 gr CO₂/100 gr of condensate oil when we increased temperature of our experiment from T = 27 °C to 50 °C.

The correlation discovered by Emera and Sarma was used to validate the measured values of CO₂ solubility in condensates oil. This correlation gives calculated CO₂ solubility values in condensates oil samples. Notably, the computed solubility data agreed with the actual data under the experimental circumstances of this investigation. These findings highlight the outcome of collision frequency and also temperature of CO₂ solubility in condensate oil and validate the correlation planned by Emera and Sarma for calculating CO₂ solubility in the given experimental settings.

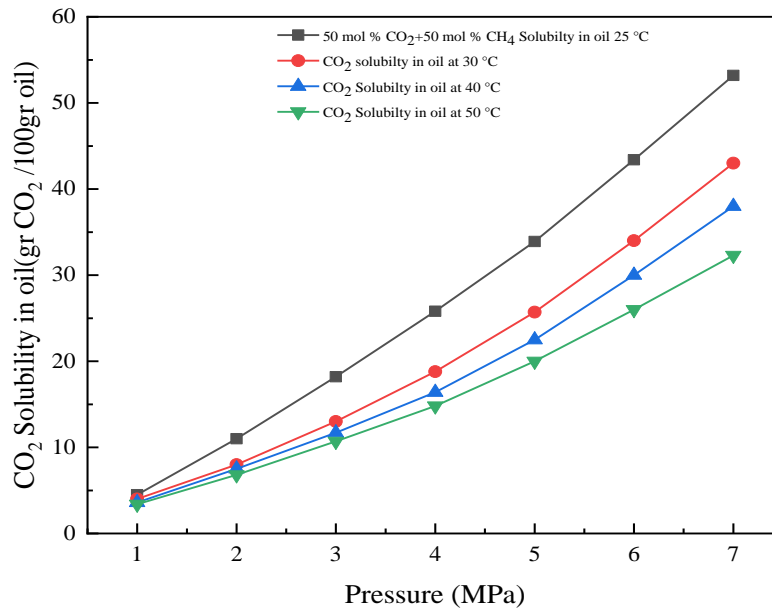


Figure 53-2 Measured CO₂+ CH₄ solubility and calculated CO₂+ CH₄ solubility along verses Pressure at different temperatures.

Bubble point pressure, temperature, also condensate API gravity all impact CO₂ solubility in condensate oil or in DI water. The solubility of carbon dioxide in condensate increases with pressure and oil API gravity, whereas it declines along with temperature increases. Other parameters influencing CO₂ solubility in oil, such as oil composition and CO₂ liquefaction pressure, have also been discovered in the literature. Because of its higher diffusion coefficient, gaseous CO₂ is thought to be more soluble in oil than liquid CO₂. The enhanced molecular velocity and distance travelled by gaseous CO₂ molecules is responsible for this. As a result, gaseous CO₂ molecules may flow more readily, mix with the oil interface, and dissolve into the oil phase, resulting in quicker diffusion rates.

I have used a created a model that predicts CO₂ solubility in oil depending on different parameters such as pressure, oil specific gravity, temperature, oil composition (represented by oil molar mass) and also CO₂ pressure required for liquification. Figure 4-2 depicts a graph of CO₂ solubility in several oil samples under numerous operational settings using this approach. Notably, the solubility of CO₂ in crude oils rose as temperature declined at the same saturation pressure.

3.1.3 CO₂ solubility in condensate oil and swelling factor

The solubilities of carbon dioxide for the carbon dioxide-Condensates oil system was find out at two temperatures, $T = 25\text{ }^{\circ}\text{C}$ and $50\text{ }^{\circ}\text{C}$, used a maximum pressure, temperature of medium range of PVT cell. The setup used for experimental determination of the solubility of CO₂ in condensate oil is portrayed schematically in the figure. The equipment was complete up of a tall-pressure CO₂ cylinder, a high-pressure cell with clear windows, and a magnetic stirrer. For the solubility measurement tests, this apparatus was put in an air bath to sure that an invariable temperature was keep constant using a temperature controller. The crude oil sample, and also a magnet, and an electric stirrer were all present in the visual cell. By triggering convective mass transfer, stirring the oil sample significantly sped up the breakdown of carbon dioxide in the condensate oil. A digital pressure gauge was used to keep track of the pressure internally in the PVT cell.

Four invariable temperatures between $T = 27$ and $50\text{ }^{\circ}\text{C}$ were selected to test the solubility of Carbon dioxide in condensate as a light oil at various equilibrium pressures. Prior to each solubility measurement, the temperature of the air bath is fixed to the compulsory test range, T . A 25 cm^3 volume of crude oil was used to charge the high-pressure cell. The pressure cell was subjected to a predetermined pressure, P_i , using CO₂. As the CO₂ dissolved into the crude oil, the pressure inside the cell was allowed to settle. When the pressure inside the cell steadied and there was no longer a pressure fall ($P = 0.8\text{ KPa/day}$) or when the ultimate CO₂ pressure, P_f , was attained, the test was deemed to be complete. Finally, a variety of pictures and image processing technologies were used to determine the initial and final CO₂ volumes in the visual cell, $V_{\text{CO}_2,i}$ and $V_{\text{CO}_2,f}$. The amount of soluble CO₂ in 100 gr of the condensate oil sample divided by its total mass was used to calculate solubility throughout the experiment. It was estimated using the mass balance and also beside that used an ideal gas equations for the dissolving mechanism. The ultimate volume of the crude oil in the cell, $V_{o,f}$, which is the consequence of two process—CO₂ dissolution in the condensates and the extraction of light and also medium hydrocarbon groups from the oil to the CO₂ phase—is used to calculate the swelling factor, abbreviated as SF. The difference between the starting condensate volume $V_{o,i}$ at experimental pressure and temperature and the end CO₂-saturated oil volume $V_{o,f}$ at those same conditions is used to calculate SF.

$$SF = \frac{V_{o,f}(P,T)}{V_{o,i}(P_{atm},T)}$$

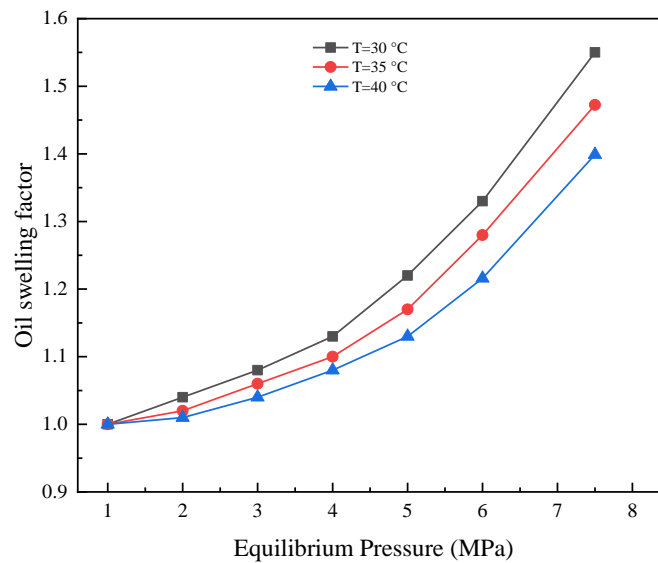


Figure 63-3 Measured oil swelling factor versus Equilibrium Pressure between CO₂ and Light oil at temperature T= 30, 35, 40 °Cs.

The relationships created by Emera and Sarma, that was discovered to be much precise and accurate than other correlations available, were also used to derive CO₂ solubility values. In connection to the pressure of saturation, temperature, oil specific's gravity, and oil molar mass, the models were displayed. Their construction involved a genetic algorithm. The number of carbon dioxide solved in the condensate oil and volume of light hydrocarbons removed into the CO₂-rich vapor phase were used to compute the swelling factor.

The swelling factor, SF, which indicates the increase in volume of the oil phase due to CO₂ dissolution, was examined at temperatures rises from T = 30 to 50 °C. At atmospheric pressure and the experimental temperature, the swelling factor was found to be equal to one. However, as the equilibrium pressure increased, the oil stage expanded, resulting in a swelling factor greater than one. This expansion was primarily accredited to the larger range of solubility of carbon dioxide in the condensates oil. Notably, the maximum swelling and CO₂ solubility were observed at a pressure of 6.4 MPa and an experimental temperature of T = 30 °C, where the swelling factor (SF) reached 1.3571 and the maximum CO₂ solubility ($\chi_{o,max}$) was 33.11 gr CO₂/100 gr of oil.

Table 3-1 :Extraction pressure measured, max. CO₂ solubility, and oil swelling factor for swelling tests conducted at various experimental temperatures.

Experimental Temperature, T _{exp} (°C)	Measured extraction pressure, P _{ext} (MPa)	Maximum CO ₂ solubility, $\chi_{o,max}$ (grCO ₂ /100grOil)	Maximum oil swelling factor, SF _{max}
30	6.0	33.8	1.37
35	6.8	31.4	1.31
40	7.8	33.45	1.27

The swelling factor, or SF, which denotes the volume increase of the oil phase as a result of CO₂ dissolution, was studied at temperatures between 30 and 40 °C. The swelling factor was found to be one at the experimental temperature and ambient pressure. The expansion of the oil phase caused the equilibrium pressure to rise, which resulted in a swelling factor greater than one. The fundamental reason for this expansion was the highest solubility of CO₂ in the condensates oil. The swelling factor (SF) reached 1.4130 and the highest CO₂ solubility ($\chi_{o,max}$) was 34.0 gr CO₂/100 gr of oil, respectively, at a pressure of 6.3 MPa and an experimental temperature of 30 °C, which is noteworthy. The oil swelling factor curves showed a considerable drop at the extraction pressure (P_{ext}) during the swelling/extraction experiments. A significant amount of the crude oil's light to medium hydrocarbon groups were removed and vaporized by CO₂ at this pressure, creating a phase that was high in CO₂. Table 3.5 presents the results of the determination of the maximum CO₂ solubility, maximum oil swelling factor, and extraction pressure for a range of operating temperatures. The CO₂-oil interaction was principally characterized by the extraction of the remaining light to medium hydrocarbon components, which resulted in a shrinkage in the oil phase and a decrease in the oil swelling factor, beyond the extraction pressure. Due to the development of a high-density CO₂-rich phase with improved extraction capabilities, this reduction persisted as the equilibrium pressure grew even further.

The swelling/extraction curve was shown to be affected by the experimental temperature. According to the findings, the maximum swelling factor reduced as temperature rose, and the CO₂-oil system's extraction pressures were higher at higher temperatures than they were at lower temperatures. When the temperature was 40 °C, the extraction pressure was P_{ext} = 6.8 MPa. When the temperature was 30 °C, it was P_{ext} = 6.0 MPa.

3.1.4 Diffusion of CO₂/CH₄ in light oil

Three main mechanisms—swelling, viscosity reduction, and decreased residual oil saturation—have all been shown to enhance oil recovery. The interaction of CO₂ and oil during CO₂ injection processes increases displacement efficiency. At the pore scale, diffusion is essential for mass movement. In order to attain chemical potential equilibrium, molecules must migrate from high concentration regions to low concentration regions via a process known as diffusion. The rate of mass transfer in solvent-assisted recovery procedures is an important aspect in determining the viability of recovering light oil. The diffusion coefficient, on the other hand, is an important metric in quantifying the mass transfer process.

The pressure-time curves produced from the methane-oil and CO₂-oil systems in our experiment are shown in Figures 3 and 4. Some temperature variations were noted during the trial, especially on evenings when the air conditioning wasn't running. Periodic segments of rising pressure were produced as a result of these oscillations. But over all, a downward pressure tendency was seen throughout time.

A curve can be seen in the graphs, which represents the early phase of gas dissolution in the oil. It's typical to refer to this phase as the "incubation period." As shown in Figures 5 and 6, the experiments done base data were plot as a semi logarithmic graph. and the least square approach was used to generate a straight line after this first phase of rapidly falling pressure.

It is significant to note that due near the partial linearity of the pressure-time relationship, not all experimental data points could adequately denoted by a conventional line on the semi-logarithmic axis. However, by calculating the straight line's slope representing the linear component of the data, the diffusion coefficients of gases in the oil must derived. It was necessary to ascertain the equilibrium pressure, P_{eq} , in order to create the semi-logarithmic graphs shown in Figures 5. The experimental pressure-time curve was extrapolated in order to determine this value. The ultimate pressure was close to the P_{eq} value, but it would have taken much longer to attain the precise equilibrium. This raises a crucial issue: how would any estimation error in P_{eq} affect the predicted diffusion coefficient?

Different values of P_{eq} were taken into consideration in order to gauge how sensitive the computed diffusion coefficient, D_{AB} , is to the estimated value of P_{eq} . The plots of

the experimental data with various P_{eq} values are shown in Figures 7 and 8. It is clear that the graphical technique does not have the sensitivity needed to detect slight changes in the P_{eq} value. P_{eq} can be varied to get similarly good linear fits. In Tables 2 and 3, the corresponding computed values of DAB for these presumptive P_{eq} values are shown. Notably, it was discovered that DAB is extremely susceptible to the presumptive P_{eq} value. As a result, relying simply on the graphical method to calculate DAB is unreliable unless P_{eq} 's value is empirically determined with little to no uncertainty.

Table 3-2 Diffusion co-efficient of CO2 and CO2 + CH4 in light oil

Components	Initial Pressure (KPa)	Equilibrium pressure in (KPa)	Temperature °C	Values of Slope	Diffusion Co-efficient (m2/sec)
CO2	3500	1400	40	2.0 *10-5	8.11*10-8
CO2+CH4	2040	500	35	3.0 *10-5	1.22*10-7
CO2+CH4	1200	200	40	3.0 *10-5	1.18*10-7

$$D_{AB} = \frac{4z_0^2}{k_1 \pi^2}$$

DAB = diffusion coefficient, m2 /sec

Zo = altitude of the oil in PVT cell, cm

K1 = coefficient

Experiment Results:

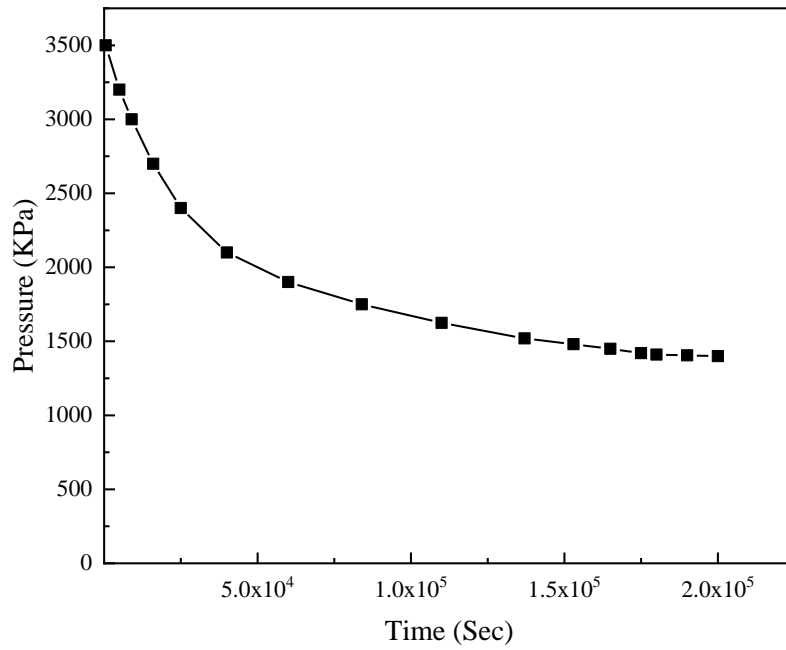


Figure 3-4 Calculated diffusion co-efficients of CO₂ measured through Pressure verses times.

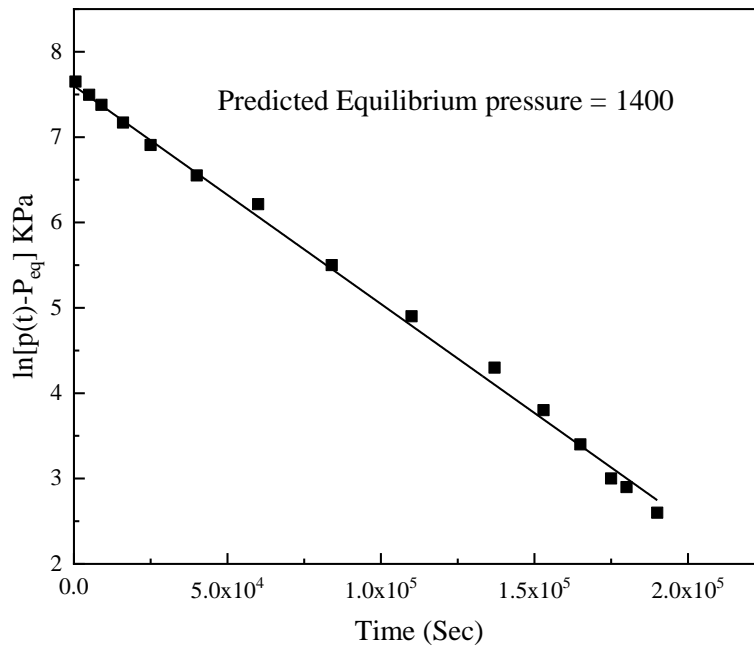


Figure 3-5 Plot of Pressure verses time for Carbon dioxide oil system.

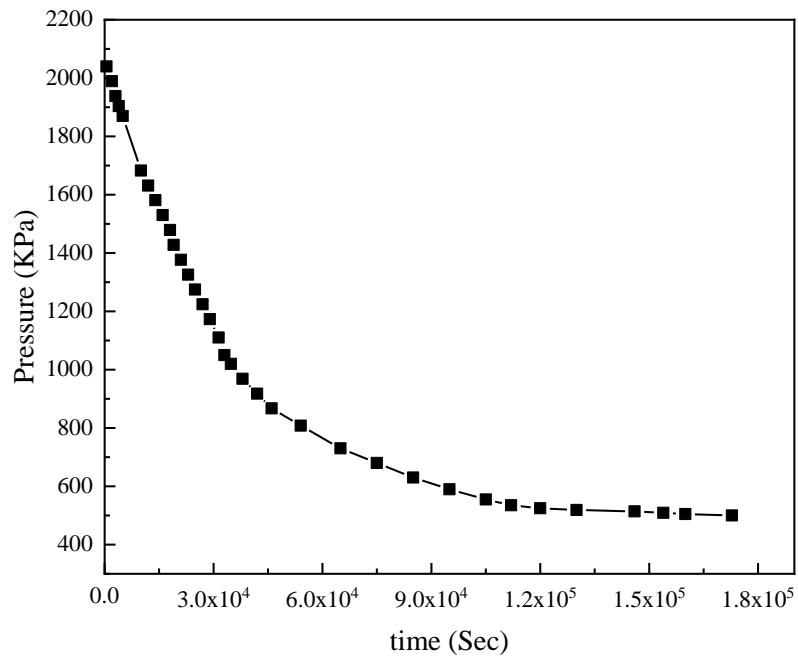


Figure 3-6 Calculated diffusion co-efficient of CO₂ measured through 2040 KPa initial Pressure verses times.

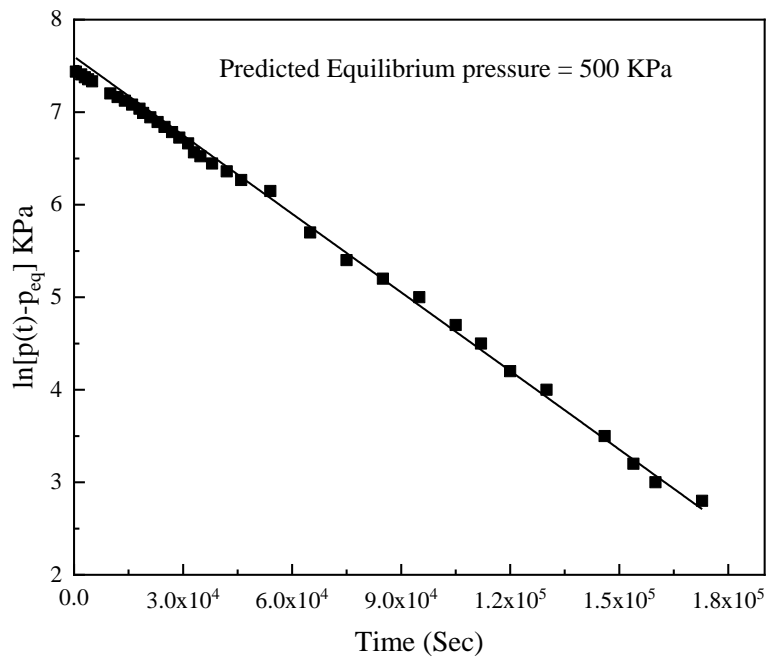


Figure 3-7 Plot of Pressure verses time for CO₂ Oil system with low initial pressure.

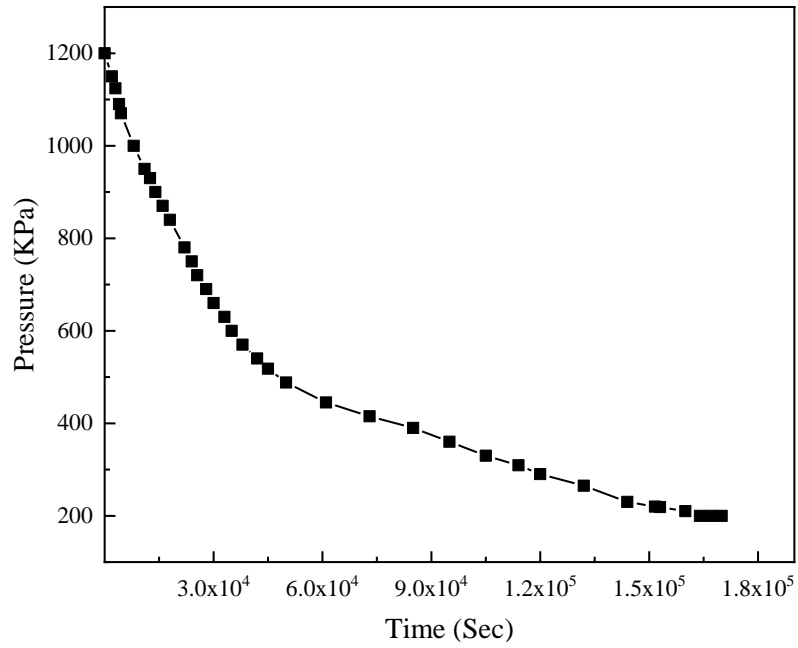


Figure 3-8 Calculated diffusion co-efficients of CO₂+CH₄ measured between Pressure and times.

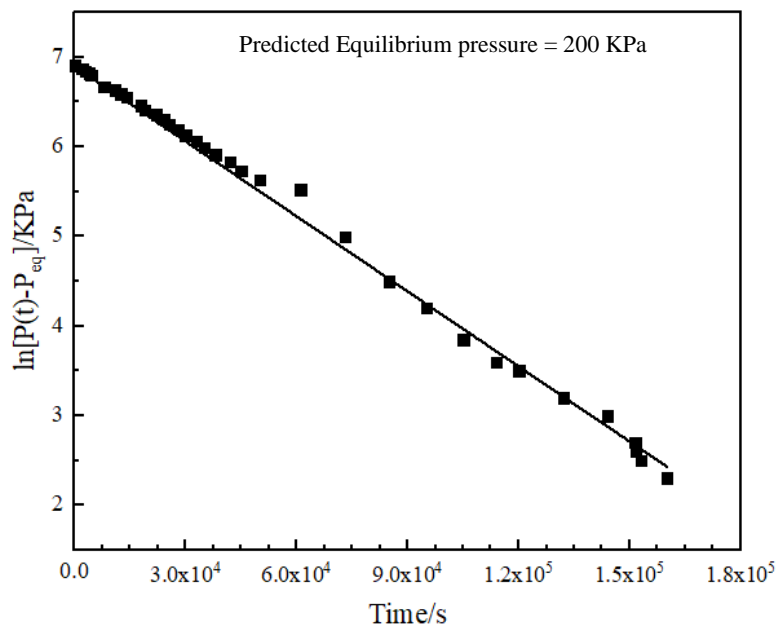


Figure 3-9 Plot of Pressure verses time for CO₂+CH₄ Oil system

Chapter 4

4.1 Conclusion

In this study, we conducted comprehensive investigations into carbon dioxide (CO₂) solubility in condensate oil and salt-water(5-10 wt.%) systems, considering various influential factors such as temperature, pressure, and stirring. Our findings shed light on the solubility behavior of CO₂ and have significant implications for applications in enhanced oil recovery (EOR) technologies.

In the CO₂-oil system, we observed that increasing pressure led to the Maximum carbon dioxide solubility in the crude oil while increasing temperature had the opposite effect. This knowledge is crucial for EOR techniques, as understanding the solubility behavior allows for more accurate predictions of CO₂ injection scenarios. Additionally, the identification of optimal pressure and temperature situations for maximizing the solubility of Carbon dioxide and also swelling factor provides valuable insights for EOR strategies.

Furthermore, we investigated the CO₂ solubility in brine systems and measured those maximum pressures resulted in a significant increase in CO₂ solubility until reaching a plateau. This information is vital for CCS applications, where CO₂ is injected into bottomless salt-Water reservoirs for lengthy term storing. Our results emphasize the importance of considering pressure effects when designing CCS projects and estimating the storage capacity of geological formations.

The diffusion coefficient analysis revealed that gaseous CO₂ had higher solubility in oil compared to liquid CO₂ due to its superior diffusion characteristics. This finding highlights the role of diffusion in CO₂ dissolution and suggests that gas-phase CO₂ may be more efficient for EOR applications. Moreover, CO₂ and CH₄ use with oil to investigate the solubility in condensate oil along with pressure changes and also temperature differences. The utilization of this model provides a practical tool for predicting CO₂ solubility under different operating conditions, enabling efficient planning and optimization of EOR and CCS processes.

References

REFERENCES

- [1] IEA, “World Energy Outlook 2009,” Outlook, no. November, 2009, [Online]. Available: http://www.oecd-ilibrary.org/energy/world-energy-outlook-2009_weo-2009-en
- [2] P. S. Kang, J. S. Lim, and C. Huh, “Screening criteria and considerations of offshore enhanced oil recovery,” *Energies*, vol. 9, no. 1, pp. 1–18, 2016, doi: 10.3390/en9010044.
- [3] N. Mosavat and F. Torabi, “Performance of secondary carbonated water injection in light oil systems,” *Ind. Eng. Chem. Res.*, vol. 53, no. 3, pp. 1262–1273, 2014, doi: 10.1021/ie402381z.
- [4] J. W. Henry and R. W. Stone, “End-user perceptions of the impacts of computer self-efficacy and outcome expectancy on job performance and patient care when using a medical information system,” *Int. J. Healthc. Technol. Manag.*, vol. 1, no. 1–2, pp. 103–124, 1999, doi: 10.1504/ijhtm.1999.001056.
- [5] N. Mosavat and F. Torabi, “Application of CO₂-saturated water flooding as a prospective safe CO₂ storage strategy,” *Energy Procedia*, vol. 63, pp. 5408–5419, 2014, doi: 10.1016/j.egypro.2014.11.571.
- [6] M. Algharaib, “Potential applications of CO₂-EOR in the middle east,” *SPE Middle East Oil Gas Show Conf. MEOS, Proc.*, vol. 2, no. March, pp. 757–767, 2009, doi: 10.2118/120231-ms.
- [7] S. Mahdavi, “Investigation of Carbonated Water Injection (Cwi) for Enhanced Oil Recovery At the Pore and Corescale,” PhD thesis, Meml. Univ. Newfoundl., no. January, p. 246, 2019.
- [8] G. Shu, M. Dong, S. Chen, and H. Hassanzadeh, “Mass transfer of CO₂ in a carbonated water-oil system at high pressures,” *Ind. Eng. Chem. Res.*, vol. 56, no. 1, pp. 404–416, 2017, doi: 10.1021/acs.iecr.6b03729.

[9] N. Mosavat, “UTILIZATION OF CARBONATED WATER INJECTION (CWI) AS A MEANS OF IMPROVED OIL RECOVERY IN LIGHT OIL SYSTEMS : PORE-SCALE MECHANISMS AND RECOVERY EVALUATION A Thesis Submitted to Faculty of Graduate Studies and Research In Partial Fulfilment of the Requirem,” no. September, p. 267, 2014.

[10] M. M. Kulkarni and D. N. Rao, “Experimental investigation of miscible and immiscible Water-Alternating-Gas (WAG) process performance,” J. Pet. Sci. Eng., vol. 48, no. 1–2, pp. 1–20, 2005, doi: 10.1016/j.petrol.2005.05.001.

[11] M. S. Picha, “Enhanced oil recovery by hot CO₂ flooding,” SPE Middle East Oil Gas Show Conf. MEOS, Proc., vol. 3, pp. 1182–1186, 2007, doi: 10.2523/105425-ms.

[12] N. N. Akinfiev and L. W. Diamond, “Thermodynamic model of aqueous CO₂-H₂O-NaCl solutions from -22 to 100 °C and from 0.1 to 100MPa,” Fluid Phase Equilib., vol. 295, no. 1, pp. 104–124, 2010, doi: 10.1016/j.fluid.2010.04.007.

[13] C. S. Matthews, “Carbon Dioxide Flooding,” Dev. Pet. Sci., vol. 17, no. PB, pp. 129–156, 1989, doi: 10.1016/S0376-7361(08)70458-8.

[14] H. O. Co, “H₂o を電子源とする co₂ の光還元における反応中間体の検討 (,” pp. 1246–1249, 2016.